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REPRESENTATION
OF
WIGLEY HULLS BY HLLSRF

David Hally

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REPRESENTATION
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WIGLEY HULLS BY **HLLSRF**

David Hally

September 1989

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Abstract

Wigley hulls have been widely used as test cases for hydrodynamic computer programs because they can be modelled exactly in the computer, and because there are extensive experimental data describing the flow around them. In this communication, it is shown how Wigley hulls can be described using the HLLSRF hull representation system. A user's guide for a Fortran 77 program which generates a HLLSRF data file for a Wigley hull is included.

Canada, French language, Spline functions, (B Splines.

(KR)

Résumé

Les coques Wigley ont été largement utilisées pour l'essai des programmes hydrodynamiques informatisés, car elles peuvent être modélisées avec exactitude par l'ordinateur et parce qu'on dispose d'une grande masse de données expérimentales relatives à l'écoulement d'eau autour d'elles. Dans la présente communication, on montre comment les coques Wigley peuvent être décrites au moyen du système HLLSRF de représentation des coques. Est inclus un guide d'utilisation du programme Fortran 77 qui génère les données d'une coque Wigley dans le système HLLSRF.

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Notation

a hull form parameter

B the hull half-breadth

$B_{n,k_x}^{(x)}$ the nth B-spline of order k_x with respect to the knot sequence $t_i^{(x)}$

$B_{n,k_y}^{(y)}$ the nth B-spline of order k_y with respect to the knot sequence $t_i^{(y)}$

D the hull depth

C_B block coefficient

k_x the order of the B-splines $B_{n,k_x}^{(x)}$

k_y the order of the B-splines $B_{n,k_y}^{(y)}$

L length between perpendiculars

N_x the number of B-splines $B_{n,k_x}^{(x)}$

N_y the number of B-splines $B_{n,k_y}^{(y)}$

p $= T/D$

$t_i^{(x)}$ the knot sequence used to define $B_{n,k_x}^{(x)}$

$t_i^{(y)}$ the knot sequence used to define $B_{n,k_y}^{(y)}$

T the hull draft

x HLLSRF non-cartesian coordinate

x_{AP} the station number of the aft perpendicular

x_{FP} the station number of the forward perpendicular

X HLLSRF cartesian coordinate

X' cartesian coordinate used to define the Wigley hull

y HLLSRF non-cartesian coordinate

Y HLLSRF cartesian coordinate

Y' cartesian coordinate used to define the Wigley hull

Z HLLSRF cartesian coordinate

Z' cartesian coordinate used to define the Wigley hull

α_{jn} spline coefficients used to define Y

β_{jn} spline coefficients used to define Z

γ_n coefficients defined in equation (2.4)

λ_n coefficients defined in equation (2.4)

μ_n coefficients defined in equation (2.4)

τ_n coefficients defined in equation (2.4)

$f_Y(x)$ function defined in equation (3.9)

$g_Y(x)$ function defined in equation (3.10)

$f_Z(x)$ function defined in equation (3.11)

$g_Z(x)$ function defined in equation (3.12)

1 Introduction

Because Wigley hulls can be represented exactly by computers, they have been widely used as test cases of hydrodynamic programs, particularly for calculations of wave resistance and boundary layer flow. Experimental data on the flow about Wigley hulls are extensive.

The hull representation system HLLSRF[1], developed at DREA for use in hydrodynamic computations, is capable of representing Wigley hulls exactly; however, the correct form for that representation is not readily apparent. In this communication the HLLSRF representation of the Wigley hull is derived.

Appendix A is a user's guide for a Fortran 77 program, WIGLEY, which implements the calculations described here.

2 The HLLSRF Hull Representation

HLLSRF uses B-splines of arbitrary order to represent hulls (see de Boor[2] for further information on B-splines). The hull representation defines a functional form for the cartesian coordinates on the hull surface and two non-cartesian hull coordinates, x and y. The cartesian coordinates are denoted X, Y, and Z; X varies between 0 and L as one goes from bow to stern; Y is the distance from the centreplane; and Z is the distance above the baseline. The HLLSRF representation relates (X, Y, Z) to (x, y) as follows.

$$X(x,y) = \frac{(x - x_{FP})L}{x_{AP} - x_{FP}} \tag{2.1}$$

$$Y(x,y) = B \sum_{j=1}^{N_y} \sum_{n=1}^{N_x} \alpha_{jn} B_{n,k_x}^{(x)}(x) B_{j,k_y}^{(y)}(y) \tag{2.2}$$

$$Z(x,y) = D \sum_{j=1}^{N_y} \sum_{n=1}^{N_x} \beta_{jn} B_{n,k_x}^{(x)}(x) B_{j,k_y}^{(y)}(y) \tag{2.3}$$

where

L is the length between perpendiculars,

B is the half-breadth,

D is the hull depth,

x_{FP} is the station number at the forward perpendicular,

x_{AP} is the station number at the aft perpendicular,

$B_{n,k_x}^{(x)}(x)$ is a B-spline of order k_x corresponding to a knot sequence $t_i^{(x)}, i = 1, \ldots, N_x + k_x$, for each $n = 1, \ldots, N_x$,

$B_{n,k_y}^{(y)}(y)$ is a B-spline of order k_y corresponding to a knot sequence $t_i^{(y)}, i = 1, \ldots, N_y + k_y$, for each $n = 1, \ldots, N_y$, and

α_{jn}, β_{jn} are coefficients.

If the spline coefficients α_{jn} and β_{jn} have the form

$$\alpha_{jn} = \gamma_j \lambda_n \quad ; \quad \beta_{jn} = \mu_j \tau_n \tag{2.4}$$

then the HLLSRF representations of the Y and Z coordinates have the form

$$Y = B f_Y(x) g_Y(y) \tag{2.5}$$

$$Z = D f_Z(x) g_Z(y) \tag{2.6}$$

where

$$f_Y(x) = \sum_{n=1}^{N_x} \lambda_n B_{n,k_x}^{(x)}(x) \tag{2.7}$$

$$g_Y(y) = \sum_{j=1}^{N_y} \gamma_j B_{j,k_y}^{(y)}(y) \tag{2.8}$$

$$f_Z(x) = \sum_{n=1}^{N_x} \tau_n B_{n,k_x}^{(x)}(x) \tag{2.9}$$

$$g_Z(y) = \sum_{j=1}^{N_y} \mu_j B_{j,k_y}^{(y)}(y) \tag{2.10}$$

HLLSRF can represent exactly any hull which can be written in the form of equations (2.1), (2.5), and (2.6) where f_Y, f_Z, g_Y, and g_Z are piecewise polynomials.

3 Representation of Standard Wigley Hulls

The class of mathematical hull forms known as Wigley hulls is usually defined as follows[3].

$$\frac{Y'}{B} = \left(1 - \frac{Z'^2}{T^2}\right)\left(1 - \frac{4X'^2}{L^2}\right)\left(1 + a\frac{4X'^2}{L^2}\right) \tag{3.1}$$

Here T is the draft and X', Y' and Z' are cartesian coordinates such that X' varies between $-L/2$ and $L/2$ as one goes from bow to stern; Y' is the distance from the centreplane; and Z' is the distance below the waterline. In terms of the HLLSRF cartesian coordinates

$$X' = X - L/2 \tag{3.2}$$

$$Y' = Y \tag{3.3}$$

$$Z' = D - Z \tag{3.4}$$

Setting $D = T$, equation (3.1) can be rewritten

$$\frac{Y}{B} = \frac{Z}{T}\left(2 - \frac{Z}{T}\right)\frac{4X}{L}\left(1 - \frac{X}{L}\right)\left[1 + a\left(1 - \frac{2X}{L}\right)^2\right] \tag{3.5}$$

The hull form parameter a may be used to vary the block coefficient, C_B, which is related to a by

$$C_B = \frac{4}{9}\left(1 + \frac{a}{5}\right) \tag{3.6}$$

The value of a must be in the range $(-1, 1)$ to produce realistic hull forms; for $a < -1$, the value of Y will be negative at some stations, while if $a > 1$, the value of Y will exceed B at some stations. Hence, the block coefficient must be in the range $(16/45, 24/45) = (0.35555, 0.53333)$.

Let $x_{FP} = -1$, $x_{AP} = 1$, and $y = Z/D$. Then from equation (2.1) one has $x = 2X/L - 1 = X'/L$ and equation (3.5) becomes

$$\frac{Y}{B} = y(2 - y)(1 - x^2)(1 + ax^2) \tag{3.7}$$

$$\frac{Z}{D} = y \tag{3.8}$$

which are of the form of equations (2.5) and (2.6) with

$$f_Y(x) = (1 - x^2)(1 + ax^2) \tag{3.9}$$
$$g_Y(y) = y(2 - y) \tag{3.10}$$
$$f_Z(x) = 1 \tag{3.11}$$
$$g_Z(y) = y \tag{3.12}$$

Both f_Y and f_Z are polynomials of fifth order or lower over the region $[-1, 1]$; therefore, they can be represented by B-splines generated by setting $N_x = 5$, $k_x = 5$, and the x-knot sequence, $t_i^{(x)}$, to be $\{-1, -1, -1, -1, -1, 1, 1, 1, 1, 1\}$. The B-splines in x are

$$B_{1,5}(x) = \frac{(1 - x)^4}{16} \tag{3.13}$$

$$B_{2,5}(x) = \frac{(1 + x)(1 - x)^3}{4} \tag{3.14}$$

$$B_{3,5}(x) = \frac{3(1 - x^2)^2}{8} \tag{3.15}$$

$$B_{4,5}(x) = \frac{(1 - x)(1 + x)^3}{4} \tag{3.16}$$

$$B_{5,5}(x) = \frac{(1 + x)^4}{16} \tag{3.17}$$

(See de Boor[2], chapter IX, for methods of generating B-splines from their associated knot sequences.) Equations (2.7), (2.9), (3.9) and (3.11) are satisfied by setting

$$\lambda_1 = \lambda_5 = 0 \quad ; \quad \lambda_2 = \lambda_4 = 1 + a \quad ; \quad \lambda_3 = \frac{4(1 - a)}{3} \quad ; \tag{3.18}$$

3

$$\tau_1 = \tau_2 = \tau_3 = \tau_4 = \tau_5 = 1 \qquad (3.19)$$

Both g_Y and g_Z are polynomials of third order or lower over the region $[0,1]$. Moreover, each vanishes at $y = 0$, so that they can each be represented by setting $N_y = 2$, $k_x = 3$, and the y-knot sequence, $t_i^{(y)}$, to be $\{0,0,1,1,1\}$. The B-splines in y are

$$B_{1,3}(y) = 2y(1-y) \qquad (3.20)$$
$$B_{2,3}(y) = y^2 \qquad (3.21)$$

Equations (2.8), (2.10), (3.10) and (3.12) are satisfied by setting

$$\gamma_1 = \gamma_2 = 1 \qquad (3.22)$$

$$\mu_1 = 1/2 \quad ; \quad \mu_2 = 1 \qquad (3.23)$$

The corresponding values of α_{jn} and β_{jn} are given in Table 1.

α_{jn}					
	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$
$j = 1$	0	$1 + a$	$4(1-a)/3$	$1 + a$	0
$j = 2$	0	$1 + a$	$4(1-a)/3$	$1 + a$	0

β_{jn}					
	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$
$j = 1$	1/2	1/2	1/2	1/2	1/2
$j = 2$	1	1	1	1	1

Table 1: α_{jn} and β_{jn} for Wigley hulls below the waterline only.

4 Wigley Hulls with Freeboard

For hydrodynamic calculations where the water surface is free, it is often useful to extend the standard Wigley hull above the waterline. This may be done by extending each station vertically. Figure 1 shows an offset diagram of a Wigley hull extended in this fashion; the additional horizontal line is the waterline.

The formula for the extended hull corresponding to equation (3.5) is

$$\frac{Y}{B} = \begin{cases} \dfrac{Z}{T}\left(2 - \dfrac{Z}{T}\right)\dfrac{4X}{L}\left(1 - \dfrac{X}{L}\right)\left[1 + a\left(1 - \dfrac{2X}{L}\right)^2\right] & \text{if } Z < T \\[3mm] \dfrac{4X}{L}\left(1 - \dfrac{X}{L}\right)\left[1 + a\left(1 - \dfrac{2X}{L}\right)^2\right] & \text{if } Z \geq T \end{cases} \qquad (4.1)$$
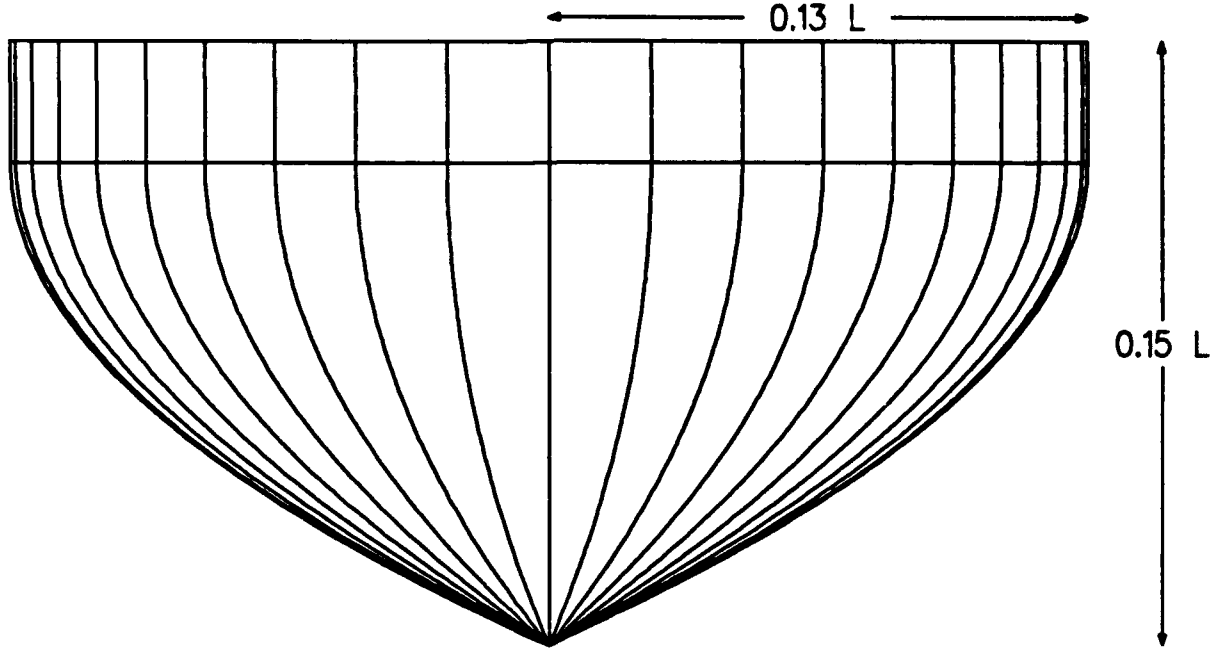
Figure 1: Offset diagram of a Wigley hull with freeboard

Retaining the identification $y = Z/D$ so that y varies between 0 and 1, the counterpart of equation (3.7) is

$$\frac{Y}{B} = \begin{cases} \dfrac{y}{p}\left(2 - \dfrac{y}{p}\right)(1 - x^2)(1 + ax^2) & \text{if } y < p \\[2mm] (1 - x^2)(1 + ax^2) & \text{if } y \geq p \end{cases} \tag{4.2}$$

where $p = T/D$. This equation is again of the form of equations (2.5) and (2.6) with f_Y and f_X unchanged from the case with no freeboard. The functions g_Y and g_Z are given by

$$g_Y(y) = \begin{cases} \dfrac{y}{p}\left(2 - \dfrac{y}{p}\right) & \text{if } y < p \\[2mm] (1 - x^2)(1 + ax^2) & \text{if } y \geq p \end{cases} \tag{4.3}$$

$$g_Z(y) = y \tag{4.4}$$

Both g_Y and g_Z are piecewise polynomials of order three or less over the region $[0, 1]$ with a single breakpoint at $y = p$. Since each vanishes at $y = 0$, they can be represented by setting $N_y = 3$, $k_x = 3$, and the y-knot sequence, $t_i^{(\nu)}$, to be $\{0, 0, p, 1, 1, 1\}$. The B-splines in y become

$$B_{1,3}(y) = \begin{cases} \dfrac{y(2p - (1 + p)y)}{p^2} & \text{for } y < p \\[2mm] \dfrac{(1 - y)^2}{1 - p} & \text{for } y \geq p \end{cases} \tag{4.5}$$

5

$$B_{2,3}(y) = \begin{cases} \dfrac{y^2}{p} & \text{for } y < p \\[2ex] \dfrac{(1-y)((2-p)y-p)}{(1-p)^2} & \text{for } y \geq p \end{cases} \qquad (4.6)$$

$$B_{3,3}(y) = \begin{cases} 0 & \text{for } y < p \\[2ex] \dfrac{(y-p)^2}{(1-p)^2} & \text{for } y \geq p \end{cases} \qquad (4.7)$$

Equations (2.8), (2.10), (4.3) and (4.4) are satisfied by setting

$$\gamma_1 = \gamma_2 = \gamma_3 = 1 \qquad (4.8)$$

$$\mu_1 = p/2 \quad ; \quad \mu_2 = (1+p)/2 \quad ; \quad \mu_3 = 1 \qquad (4.9)$$

The corresponding values of α_{jn} and β_{jn} for the Wigley hull with freeboard are given in Table 2.

α_{jn}					
	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$
$j = 1$	0	$1 + a$	$4(1-a)/3$	$1 + a$	0
$j = 2$	0	$1 + a$	$4(1-a)/3$	$1 + a$	0
$j = 3$	0	$1 + a$	$4(1-a)/3$	$1 + a$	0
β_{jn}					
	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$
$j = 1$	$p/2$	$p/2$	$p/2$	$p/2$	$p/2$
$j = 2$	$(1+p)/2$	$(1+p)/2$	$(1+p)/2$	$(1+p)/2$	$(1+p)/2$
$j = 3$	1	1	1	1	1

Table 2: α_{jn} and β_{jn} for Wigley hulls with freeboard.

5 The Quadratic Wigley Hull

The Wigley hull for which $a = 0$ is especially simple because Y is quadratic, not quartic, in X'/L. It is sometimes called the quadratic Wigley hull. Because Y is quadratic in X'/L and hence in x, the x-B-splines need only be of third order rather than fifth order. Because B-splines become more costly to evaluate as the order increases, and because this particular form of the Wigley hull is widely used, it is worth generating a third order representation of it.

Since the dependence of Y upon y is unchanged, it is only necessary to consider a modification in the B-splines which depend on x. From equations (3.9) and (3.11) with $a = 0$, one has

$$f_Y(x) = (1 - x^2) \tag{5.1}$$
$$f_Z(x) = 1 \tag{5.2}$$
$$\tag{5.3}$$

These functions must be represented in terms of B-splines of order three in x. Setting $N_x = 3$, $k_x = 3$, and the knot sequence $t_i^{(x)}$ to be $\{-1, -1, -1, 1, 1, 1\}$, one has

$$B_{1,3}(x) = \frac{(1 - x)^2}{4} \tag{5.4}$$

$$B_{2,3}(x) = \frac{(1 - x^2)}{2} \tag{5.5}$$

$$B_{3,3}(x) = \frac{(1 + x)^2}{4} \tag{5.6}$$

Equations 2.7, (2.9), (5.1) and (5.2) are satisfied by setting

$$\lambda_1 = \lambda_3 = 0 \quad ; \quad \lambda_2 = 2 \tag{5.7}$$

$$\tau_1 = \tau_2 = \tau_3 = 1 \tag{5.8}$$

The corresponding values of α_{jn} and β_{jn} for the Wigley hull without freeboard and with freeboard are given in Tables 3 and 4.

6 Concluding Remarks

The spline coefficients necessary to represent Wigley hulls using HLLSRF have been derived. The Wigley hulls can be represented with or without freeboard. Once Wigley hulls have been represented in this form, the HLLFLO[4] suite of hydrodynamic programs can be used to predict the flow around them.

α_{jn}			
	$n = 1$	$n = 2$	$n = 3$
$j = 1$	0	2	0
$j = 2$	0	2	0

β_{jn}			
	$n = 1$	$n = 2$	$n = 3$
$j = 1$	1/2	1/2	1/2
$j = 2$	1	1	1

Table 3: α_{jn} and β_{jn} for quadratic Wigley hulls below the waterline only.

α_{jn}			
	$n = 1$	$n = 2$	$n = 3$
$j = 1$	0	2	0
$j = 2$	0	2	0
$j = 3$	0	2	0

β_{jn}			
	$n = 1$	$n = 2$	$n = 3$
$j = 1$	$p/2$	$p/2$	$p/2$
$j = 2$	$(1+p)/2$	$(1+p)/2$	$(1+p)/2$
$j = 3$	1	1	1

Table 4: α_{jn} and β_{jn} for quadratic Wigley hulls with freeboard.

8

Appendix A User's Guide for Program WIGLEY

Purpose: The program WIGLEY creates a HLLSRF data file for a Wigley hull with or without freeboard.

Input: All input to the program is entered interactively by the user. When the program starts, the user is prompted for the hull form parameter, a.

`Enter the hull form parameter =>`

The hull form parameter must be in the range (-1.0,1.0). If it is not, an error message will be written and the user reprompted. When a valid hull form parameter has been entered, the corresponding block coefficient (see equation (3.6)) is reported to the user.

Next the user is prompted for the units in which the hull dimensions are measured.

`Enter the units for the hull dimensions =>`

Any string of ten or fewer characters will do: e.g. 'ft', 'metres', or ' '.

Next the hull dimensions themselves are required.

`Enter the length between perpendiculars, the half-breadth, the depth,`
`and the draft =>`

Each of the hull dimensions must be positive and the draft must not exceed the depth. If there is an error in input, an error message will be sent and the user reprompted.

These are all the data necessary to define the Wigley hull.

Output: WIGLEY creates an ASCII file WIGLEY.HLL which contains the HLLSRF representation of the hull.

Usage: On the DREA DEC-20/60, WIGLEY can be run by typing the following commands.

`DECLARE PCL PS:<HALLY>HLLFLO,PS:<HALLY>WIGLEY`
`WIGLEY`

The first command causes the command WIGLEY to be defined in the EXEC. Typing WIGLEY then causes the program to be run. The program can be run again simply by repeating the command WIGLEY.

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3. W. C. S. Wigley, "The Wave Resistance of Ships" (Congrès International des Ingenieurs Navals, Liège, 1939).

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Wigley hulls have been widely used as test cases for hydrodynamic computer programs because they can be modelled exactly in the computer, and because there are extensive experimental data describing the flow around them. In this communication, it is shown how Wigley hulls can be described using the HLLSRF hull representation system. A user's guide for a Fortran 77 program which generates a HLLSRF data file for a Wigley hull is included.

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